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NIKOLA TESLA
THE FOUNDER OF HIGH-FREQUENCY AND RADIO TECHNOLOGY*
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Tesla's radio research began in 1891 and extended over a period of more than 10 years. During this ten-year period, all the essential foundations of radio technology were established, with the exception of the vacuum tube, which was developed later. Tesla began his first radio experiments almost simultaneously with his experiments with high-frequency currents, as he made the important discovery during these experiments that simple wires without return conductors were sufficient for transmitting high-frequency currents. Since these experiments showed that not only electric lamps but also electric motors could be operated with just a wire, Tesla very quickly came up with the idea of using the Earth and its atmosphere instead of a wire, thus becoming independent of power lines Tesla was convinced from the outset that sufficient amounts of energy could be transmitted in this way, if not for incandescent lighting and motor drives, then certainly for wireless signal transmission over very long distances. His first experiments already showed that the realization of wireless signal transmission using high-frequency currents of sufficiently high voltage was possible and that the distances to which such wireless signals could travel depended primarily on the amount of high-frequency energy set in motion. His experiments in early 1891, in which he was able to make sufficiently evacuated tubes glow in a strong high-frequency field without any wire connections, also contributed to Tesla's decision to begin his radio research simultaneously with his other research in the field of high-frequency and high-voltage technology.

1. TESLA'S HIGH-FREQUENCY RESEARCH

Tesla's high-frequency research is directly related to his three-phase alternating current system. While developing his three-phase generators and motors for higher frequencies, he already conceived the idea of building high-frequency generators in 1888, since he was working on these new research opportunities and foresaw new discoveries in these areas. For two years (1889-1890), he constructed ever new types of high-frequency generators, thereby laying the foundations for a new dynamo technology that later achieved great development and importance. With these machines, Tesla generated high-frequency currents of 10,000-20,000 cycles. His basic patents 447,920-21 from 1890 show the various paths Tesla had taken to develop the highest possible frequencies. The first type of these machines consisted of an alternating current generator with several hundred stationary poles (up to 400) and a moving armature. A power output of 2-3 kilowatts at

10,000 cycles could easily be obtained from such a machine. Many other types were built for higher power outputs and cycle counts Tesla built high-frequency generators with stationary armature coils and rotating field magnets, with stationary field magnets consisting of two circular parts with annular grooves and a rotating armature, and also other types in which Tesla completely eliminated rotating coils by using only a wrought-iron body without any wire as the rotating part. To increase the frequencies thus obtained, he also utilized his invention of frequency amplification in asynchronous generators, which he had first described in patent 390,725 of October 1888. The research into high-frequency phenomena undertaken with these machines alone yielded astonishing results.

However, Tesla felt that high-frequency currents of several million cycles per second would yield very different results. After unsuccessful attempts to generate significantly higher frequencies with high-frequency dynamo machines, he conceived the idea in 1890 of combining a spark gap with a capacitor and a self-induction coil, thus creating the first system for generating high-frequency energy, which delivered millions of cycles of weakly damped oscillations (basic patent 462,418, dated February 4, 1891). This was the starting point for further research carried out between 1891 and 1893, which led to the invention of the Tesla coil (basic patent 454,622, dated April 25, 1891), the Tesla oscillator, loosely coupled high-frequency circuits, resonant circuits, the high-frequency arc lamp, and many other inventions and discoveries.

In the following five years, Tesla significantly developed and expanded his high-frequency work. More than twenty fundamental patents relating to various methods and apparatuses for generating Tesla currents and to many high-frequency phenomena were developed and obtained in a short time. In these patents and in the scientific lectures Tesla gave in America in 1891 and 1893 and in Europe in 1892, all these methods and inventions are described and made available to the public. The methods of generating oscillations with the rotating spark gap, with the series spark gap with many small sparks, with the high-frequency arc with magnetic and mechanical arc quenching with spark quenching in a gas atmosphere, as well as high-frequency oscillation generation in a vacuum tube and also by other means, are described in detail.

In this work of Tesla's, several main problems can be distinguished, which he strove to solve completely. We will summarize them as follows:

1) The problem of efficiency in converting large amounts of energy and the problem of generating weakly damped and undamped oscillations of any period, energy, and voltage.

2) The problem of resonance in coupled oscillating circuits, and

3) the problem of obtaining free and amplified oscillations in the working circuit.

The complete solution of these fundamental problems represented a monumental task, even for Tesla, who was inexhaustible in finding new ideas, and one that would consume his full energy for many years His efforts were, however, fully rewarded by tremendous results, for with his ever-improving apparatus, especially with his rotary oscillators with 1,000 to 100,000 and more spark quenching per second, he achieved as early as 1896 that he could convert any quantity of electrical energy, whether from direct current or alternating current machines, into undamped or very weakly damped oscillations of any period with an efficiency of more than 85%. By loosely coupling the movable coils of the Tesla transformer and precisely adjusting the natural frequency of the circuits using variable capacitors and adjustable coils, he achieved the desired resonance between several high-frequency circuits, as well as complete freedom from oscillation of the secondary circuit. Furthermore, by using spiral-shaped transformer coils, oil-filled capacitors, and oil-filled transformers, he achieved enormous amplification of the amplitude of the free oscillations and very high voltages in the working circuit.

This new technique had been developed for various practical purposes, of which we will mention only the most important below:

1) Application of high voltages for power transmission purposes. (Tesla's basic patent for the use of oil at high voltages 464,667).

2) Application of Tesla currents for economical lighting, which led to the invention of the incandescent lamp with a metallized carbon filament, the metal filament lamp, the neon lamp, etc

3) Introduction of Tesla currents into electromedicine. Tesla's early high-frequency research showed that high-frequency currents produce very weak physiological effects and that they could be used to excellent effect for electromedical purposes. Tesla's publications on this topic in early 1891 aroused great interest in the scientific community and led to in-depth investigations. The renowned Professor D'Arsonval, among others, devoted himself particularly to the application of Tesla currents in high-frequency therapy. Soon after, we see the application of Tesla currents in electromedicine realized under the names diathermy and d'Arsonvalization. Today, Tesla currents are of great importance in medicine.

4) Use of Tesla currents for various technical applications, especially for ozone and atmospheric nitrogen production and for metallurgical purposes.

2. TESLA'S RADIO RESEARCH

The most important application of Tesla currents is radio technology, for which Tesla spent years developing his high-frequency apparatus for very high power. Before we delve into Tesla's radio research, however, we want to briefly acknowledge the merits of his predecessors, Hertz and Branly.

The great German physicist Heinrich Hertz published his classic experiments around the same time that Tesla announced his three-phase current system to the world. In his experiments with a spark oscillator, Hertz had generated highly damped electromagnetic oscillations that propagated into space as electromagnetic waves and could be detected at distances of 10-20 m. These experiments provided proof of the correctness of Maxwell's electromagnetic theory The apparatus used was technically very primitive, so that only the trained eye of the great physicist could observe tiny sparks in a resonator at short distances in a completely dark room. However, these sparks were sufficient to prove the theory and establish the connection between electricity and light phenomena as described in the theory. Hertz's experiments were unusable for radio technology for two reasons: 1) Hertz's high-frequency energy consisted of highly damped oscillations and was lost at distances of over 20 meters, and 2) the generated short waves, approximately 1 meter in length, traveled in straight lines like light rays. Renowned physicists repeated Hertz's experiments with even shorter wavelengths, as they all strove to establish an even closer connection between electricity and optics by using ever shorter wavelengths, down to a few millimeters. Wireless signal transmission was not considered at this time.

It was not until 1891 that the French physicist Branly developed an apparatus, the so-called coherer, which significantly facilitated the investigation of the new phenomena introduced by Hertz. This invention provided a highly sensitive device that made it much easier to detect electromagnetic waves at distances of about 20 meters than the insensitive Hertzian resonator. Now Hertzian experiments could easily be carried out even in well-lit rooms. However, Branly's invention did not form the basis of radio technology, because Branly also worked with Hertzian oscillations and thus had no way of considering long distances. In his experiments, too, the high-frequency energy was lost outside his laboratory and could only be detected within a single room. This explains why Branly's invention, from a practical standpoint, meant little for signal transmission, as well as

Hertz's opinion that wireless signal transmission was not possible with his electromagnetic oscillations.

From these experiments by Hertz and Branly to radio technology, there was still a long way to go; many more discoveries, inventions, and research projects had to be made before the foundations of radio technology were laid. Tesla accomplished this feat. His achievement enabled the practical application of his inventions for the construction of large radio stations and for the creation of the radio technology and industry that later developed to great prominence. Nevertheless, the work of Hertz and Branly deserves due recognition tributes must be paid, because their work also influenced Tesla, and we must therefore recognize these two researchers as forerunners of radio technology

a. Tesla's Basic Plan of Radio Technology 1892-1893
   Tuned Wireless Telegraphy 1897

In his radio research, Tesla encountered many major problems of radio technology right from the start, which he fully solved in the course of his research.

The first major problem in radio technology is the generation of high frequencies of arbitrary energy in the form of undamped or weakly damped oscillations, and we have already discussed how Tesla solved this problem through a whole series of inventions. His rotary oscillators proved to be the best means of generating suitable oscillations in his radio experiments, and it has already been mentioned that with such oscillators he was able to achieve up to 100,000 or more spark quenchings per second, and so economically that the apparatus operated with an efficiency of 85%.

In this way, Tesla generated oscillations of hundreds of thousands and millions of periods that were continuous and undamped, or very weakly damped.

The second problem was how to radiate high-frequency oscillations through a system over the greatest distances, i.e., how to propagate the effect of high-frequency energy over the greatest distances on the globe.

The third problem was to capture fractions of the high-frequency energy over long distances and utilize them in suitable devices. Further problems involved tuning the transmitting and receiving stations to resonance, eliminating interference from other stations, rectifying and amplifying the received waves, and other tasks.

The problem of transmitting radio waves over very long distances was solved by open resonant circuits and by selecting suitable wavelengths. As early as his lecture at the Royal Institution in London in 1892, Tesla first presented his basic plan for radio technology to the scientific community. This plan consisted of generating and transmitting high-frequency currents in an open resonant circuit comprising the ground wire, the secondary coil of the Tesla coil, and an insulated wire (antenna) extending to a certain height. A similar arrangement, also consisting of an open high-frequency circuit to which the operating circuit is inductively coupled, is used at the receiving station. In addition to this basic plan, Tesla presented a vacuum detector in the same lecture, which was so sensitive that it could respond to the weakest electromagnetic effects. He expressed his conviction that with such a device, signals could be sent at any desired speed through submarine cables, and that even the exchange of thoughts over long distances without wires could be made possible.

Tesla described his basic plan in more detail in his lecture to the Franklin Institute in 1893 in connection with his high-frequency oscillations and expressed that the distances to which wireless signals could travel and can be transmitted, depend solely on the magnitude of the high-frequency energy set in motion, and that he is already working on generating the necessary high-energy high-frequency apparatus for these purposes. In this lecture, he already emphasizes the importance of tuning both stations to resonance and announces the means for doing so.

In the same year, as well as in the next two years, Tesla conducted various resonance experiments with different wavelengths in his laboratory, as well as other radio research, the purpose of which was to tune any number of high-frequency circuits so that they all respond only to a specific wavelength and that, in a wirelessly controlled mechanism, arbitrary movements are carried out independently of one another by individual circuits and relays. For this purpose, a radio transmitting station was built in his laboratory, capable of generating various wavelengths, from about one hundred to several hundred meters, and several automata were built with many circuits tuned to different waves, the individual movements of which were controlled by the radio station These devices served Tesla to completely solve the tuning problem, one of the most important problems in radio technology. Tesla achieved this solution by creating highly sensitive, interconnected high-frequency circuits whose individual wavelengths could be precisely adjusted by means of adjustable variable capacitors and self-induction coils. For receiving radio waves and for repeating the same movements of individual components of the automata, Tesla initially developed the rotating coherer, which proved to be very sensitive and reliable in all his radio experiments. Later, however, he developed the contact detector.

In his radio research, Tesla thus systematically pursued several goals and simultaneously engaged in diverse activities, which can be characterized as follows:

1) The constructive development of Tesla oscillators to obtain an apparatus that would convert low-frequency electrical energy into high-frequency energy of any period with high efficiency. These oscillators should enable radio experiments on a large scale and over very long distances.

2) The constructive development of various high-frequency circuits that can be precisely tuned to one another so that any interference from other waves, i.e., from other radio stations, can be eliminated, in order to enable a receiving station to respond on any specific wavelength, or to enable any number of circuits of a receiving station to perform many movements of individual parts of a mechanism simultaneously or sequentially

3) The development of a receiving apparatus capable of responding reliably to radio signals even at great distances, ensuring their reliable operation. In parallel, a receiving apparatus was designed to accumulate very weak amounts of energy over great distances and to utilize this accumulated energy. This apparatus should also be capable of rectifying the incoming waves as needed, in order to make them usable for receiving the human voice, i.e., for telephone purposes. These inventions were also intended to make it possible to use lower-powered transmitting stations achieving the greater ranges.

Tesla's work in the field of radio technology, beginning in 1891, therefore moved in very different directions and encompassed many fundamental problems of radio technology. All this work was carried out simultaneously with the greatest energy and with complete success.

By 1896, his work had progressed so far that at the beginning of 1897, he was able to build a larger experimental transmitting and receiving station near New York, which showed that wireless signals could be transmitted over very long distances with very low energy consumption using the Tesla radio system. In an article in the well-known journal "Electrical Review" of July 9, 1897, we find some information about these experiments, of which we will quote the following:

"Almost every inventor in the field of telegraphy has dreamed of wireless communication for years. From time to time, reports of experiments appeared in technical journals, showing that electricians generally agreed that one day we would be able to do without

power lines. Experiments had been carried out to tentatively demonstrate this possibility, but it was left to Nikola Tesla to establish the theory and prove it experimentally, namely that wireless communication is not only a possibility, but that there are no distances over which wireless communication would be impossible. After more than six years of purposeful and conscientious work, Tesla arrived at results on the basis of which we can foresee the future.

A contributor to our newspaper personally convinced himself of Mr. Tesla's fact that he is very reserved and cautious in his statements, and that wireless electrical communication is a complete reality and that the methods and principles used guarantee the reception of intelligible signals and messages between two very distant locations." Tesla has built both a transmitting and a receiving station capable of transmitting messages over very long distances, regardless of geopathic stress, obstacles, or direction. This is achieved with incredibly low energy consumption. Naturally, Tesla keeps the details of his invention secret, but we can reveal that the system is based on disrupting the electrical equilibrium using high-frequency currents. This disruption can be exploited and received by sensitive devices anywhere on Earth, irrespective of the distance between transmitter and receiver. Tesla published this plan several years ago, having already obtained satisfactory experimental results with his devices. Since then, much work remains to be done, and Tesla has devoted his unwavering attention to this subject and its solution. For various reasons, we do not wish to disclose further details at this time, but rather to confirm that Tesla has achieved wireless communication over very long distances with very low energy consumption and that distance is irrelevant for his devices, which can be built to handle high energy demands. Morse's experiment over a distance of 60 km in the field of telegraphy with wires was built on a much less secure foundation than the wireless transmissions of Tesla's experiments.

This publication of the well-known journal is a historical document. Its value cannot be overestimated. This important document also proves, purely formally, that at the beginning of 1897, Tesla experimentally conducted wireless telegraphy over very long distances with his transmitting and receiving station near New York, without regard to terrain or other obstacles. It is of particular importance that it states that with Tesla's apparatus and his system, distances, obstacles, and directions play no role, and that the experiments were carried out with very low energy.

Based on this publication of the "Electrical Review," we establish the following important historical facts:

1. At the beginning of 1897, Tesla conducted experiments with wireless telegraphy near New York with a transmitting and receiving station erected at a long distance, experiments which were also attended by representatives of the scientific community. The distance of the transmitting and receiving station was, as other reports indicate, twenty miles.

2. The experiments were carried out at frequencies of approximately two million periods per second, i.e., with a wavelength of approximately one hundred and fifty meters. Tesla worked with actual Tesla currents of high frequency and voltage and used rotary oscillators with mechanically extinguished sparks, which had been developed and perfected over many years.

3. The experiments were carried out based on Tesla's plan, which he had published several years earlier.

4. The basic plan was published by Tesla only after he had conducted experiments and obtained satisfactory results. This plan is the basic plan of radio technology and includes a ground wire, antenna, and multiple resonant circuits at both the transmitting and receiving stations.

5. Curvature of the earth, terrain obstacles, distances, and directions played no role in the experiments at the beginning of 1897.

6. The power consumption in the experiments carried out was measured and found to be very low

7. The greatest distances are possible with Tesla's wireless telegraphy system, as they depend only on the energy of the transmitting oscillator, which at that time could be built for any required energy.

8. Tesla's radio experiments date back to 1891 and have been carried out continuously ever since, with ever higher frequencies, until he perfected the apparatus to such an extent that he had reliable devices available for frequencies of two million periods and more.

These facts prove that the problem of wireless telegraphy was solved in 1897 on the basis of tuned high-frequency circuits with Tesla's high-performance quenched-spark oscillator, and that his experiments were publicly demonstrated

The apparatus and arrangements used in these experiments were already partly patented

by Tesla and partly patented by him. We will only list a few patent numbers here relating to quenched-spark oscillators, primarily 568,176/77/79/80, dated April 22, 1896. Furthermore, patent 568,178, dated July 20, 1896, also granted Tesla protection for his methods of regulating high-frequency circuits and tuning them to precise resonance. His patents 645,576 and 649,621 of 02 September 1897 relate to the protection of four resonant circuits, two at the transmitting station and two at the receiving station. From the last patent, we will quote only the second, third, seventh, and tenth of the ten patent claims as follows:

"2. The combination of a transmitting station, comprising a transmitting coil or wire, the ends of which are connected to earth and a raised wire, and a primary coil inductively coupled to these, in which the source of the electrical oscillations is contained, with a receiving station, comprising a receiving coil or wire, the ends of which are connected to earth and a raised wire, excited by the current pulses transmitted from the transmitter through the natural medium, and in turn inductively coupled to a secondary circuit containing the receiving apparatus."

"3. The combination of, on the one hand, the transmitting instruments, comprising a transformer whose secondary coil is connected to earth and a raised conductor, and the means to impose electrical oscillations on the primary coil of the transformer, and, on the other hand, the receiving instruments, which also comprise a transformer whose primary circuit is similarly connected to earth and to a raised conductor, while the receiving apparatus is connected to the secondary coil, wherein the capacitances and inductances of the two transformers must have such values as to ensure synchronism with the imposed oscillations as is specified here."

"7. The combination of a transmitting coil or wire, connected to earth and to a raised conductor, and the means for generating electrical currents or oscillations in the same, with a receiving coil or conductor similarly connected to earth and to the raised conductor, wherein the length of said coils is one quarter of the wavelength of the transmitted pulses, and the capacitances and inductances in the transmitter and receiver are such that both have the same period, as explained herein."

"10. The combination of a transmitting coil or wire, connected to earth and to a raised conductor, and a receiving circuit, the oscillation period of which is the same as that of the transmitter and similarly connected to earth and to the raised wire, wherein the raised wire has the highest voltage in the circuit, as described herein."

That the patents cited here and the results based on them and presented here justify Tesla's assertions that radiotelegraphy is possible with his system across the entire circumference of the Earth is proven by the large overseas radio stations built 10 to 15 years later, which were equipped with Tesla's apparatus and arrangements.

b. Tesla's Wireless Remote Control 1898

In 1898, Tesla conducted extensive experiments at sea near New York with a test vessel equipped with wireless remote control. Various new inventions and discoveries by Tesla were applied to this test vessel. In numerous public demonstrations, and particularly before the Patent Examining Commission, the test vessel executed all movements directed to it by a radio transmitting station located on the coast near New York over considerable distances of many kilometers. The propeller and steering were driven by electric motors powered by an accumulator battery located on the boat. All circuits were equipped with relays controlled by electromagnetic waves, and individual relays were influenced as needed to execute the necessary movements. Individual relay circuits were tuned to specific wavelengths by resonant circuitry using two high-frequency circuits, ensuring precise tuning to a specific wavelength and allowing individual circuits to respond only to that specific wavelength.

Tesla patented these circuits and designs for wireless remote control with patent 613,809 on July 1, 1898. The wireless remote control technology developed several decades later is based on these inventions by Tesla.

After completing these large experiments and the necessary large apparatus, Tesla built a large experimental radio station with a power output of 200 kW in Colorado, West America, in early 1899. At this station, Tesla conducted various radiotelegraphic and radiotelephonic experiments over distances of more than 1000 km, not only with wavelengths of a few hundred meters, but also with those of several kilometers. He was the first to discover that even kilometer-long waves, generated by high-frequency generators with approximately 35,000 cycles, were very well suited for radio purposes. These results formed the basis for the later development of the application of long waves and high-frequency generators for radio transmissions over the greatest distances on Earth.

Tesla spent over a year at this radio station, during which time he achieved significant new results. These resulted in various inventions, largely relating to different reception methods and apparatus, which were described in numerous patents. We mention here the following patents: 685,953/54/55/56, dated June 24 and August 1, 1899; 685,012, dated March 21,

1900; 725,605, dated July 16, 1900; 787,412, dated May 15, 1900; and 1,119,732, dated January 18, 1902.

In his experiments in Colorado, Tesla provided experimental evidence that his radio inventions and his radio system were suitable for a wide variety of radio applications.

Returning to New York from Colorado in the mid-1900s, Tesla endeavored to commercialize his World System. His business associates published a radio project for which, however, the time was not yet ripe. We quote the following from it:

"The World System is the result of many original discoveries to which Tesla arrived during long and continuous investigations and experiments. It enables not only the precise wireless transmission of any kind of signal, message, or character to all parts of the world, but also the connection of existing telegraph, telephone, and other signal stations without any alteration to their present equipment. With its means, for example, it can be achieved that a telephone subscriber can call and speak to any other subscriber on the globe. A very inexpensive receiver the size of a pocket watch will enable anyone, whether on land or at sea, to listen to lectures or music broadcast from any place, however distant..."

During these Colorado experiments, Tesla also conducted extensive high-voltage experiments, generating voltages of 12,000,000 volts and more. With such voltages and the high power outputs provided by his high-frequency transformers, he achieved effective wireless energy transmissions of up to 30 km at approximately 50,000 cycles, at which distances he wirelessly illuminated incandescent lamps from his radio station.

These experiments marked the culmination of Tesla's ten years of radio research, and as a consequence, industrial radio technology developed rather slowly—because Tesla's work was only slowly understood and utilized—its foundations based on Tesla's great and ingenious pioneering work.